

# Analyzing Microgram Quantities of Isolated Mitochondria in the Agilent Seahorse XFe/XF96 Analyzer

## Application Note

### Introduction

Enhanced appreciation for the role of altered mitochondrial function in tumorigenesis, aging, neurodegenerative, metabolic, and cardiovascular diseases has stimulated the development of a variety of new approaches for assessing mitochondrial function and dysfunction. As the field moves towards the discovery of mitochondrial-related molecular mechanisms that underlie disease and drugs to prevent or reverse disease development, the demand for higher throughput and more sensitive assay methods increases. The importance of drug candidate screens for mitochondrial toxicity is also recognized.

Measurement of the mitochondrial oxygen consumption rate (OCR) is valuable, since electron transport and oxidative phosphorylation consume oxygen and reflect the mitochondrial and nuclear genomes' expression of functional components of the electron transport chain.



A high-throughput assay in which both energy demand and substrate availability can be tightly controlled for mechanistic studies has been developed for the Agilent Seahorse XFe/XF96 Analyzer using isolated mitochondria. Figure 1 illustrates the general work flow for this experiment. The optimized conditions enable sensitive measurement of the OCR and proton extrusion or extracellular acidification (ECAR), by isolated mitochondria attached to the bottom of an Agilent Seahorse XF Cell Culture Microplate. This approach is uniquely capable of analyzing small quantities of material (0.4–4 µg of mitochondrial protein per well). Sequential measurement of Basal, State 3, State 4 and uncoupler-stimulated respiration or any other combination, can be made through additions of reagents from the drug injection ports of the XF assay cartridge. This technique can be particularly useful for mechanistic studies, drug screening and for enabling respiratory data to be obtained on small mitochondrial samples.

## Reagents

### Mitochondrial isolation buffer (MSHE+BSA)

The following reagents were used: 70 mM sucrose, 210 mM mannitol, 5 mM HEPES, 1 mM EGTA and 0.5 % (w/v) fatty acid-free BSA, pH 7.2.

### Mitochondrial assay solution (MAS, 1X)

The following solutions were used: 70 mM sucrose, 220 mM mannitol, 10 mM  $\text{KH}_2\text{PO}_4$ , 5 mM  $\text{MgCl}_2$ , 2 mM HEPES, 1 mM EGTA, and 0.2 % (w/v) fatty acid-free BSA, pH 7.2 at 37 °C.

**Note:** 3x stock MAS is needed for dilution of substrates, ADP, and respiration reagents.

### ADP and substrate stocks

The following substrate stocks were used: 0.5 M succinic acid, 0.5 M malic acid, 0.5 M glutamic acid, 0.5 M pyruvic acid, and 1.0 M ADP, all dissolved in  $\text{H}_2\text{O}$ , and adjusted to pH 7.2 with potassium hydroxide. Pyruvate should be made fresh the day of the assay.

### Respiration reagent stocks

The following reagent stocks were used: 10 mM FCCP, 2 mM rotenone, 5 mg/mL oligomycin, and 40 mM antimycin A in 95 % ethanol (do not use 100 % ethanol as it contains traces of benzene, which is detrimental to mitochondrial function). Combine 1.0 M ascorbate in  $\text{H}_2\text{O}$ , pH 7.2. 10 mM N1,N1,N1,N1-tetramethyl-1,4-phenylene diamine (TMPD) in  $\text{H}_2\text{O}$ , pH 7.2, with an equimolar concentration (10 mM) ascorbate to ensure TMPD remains reduced.

All reagents were stored at  $-20\text{ }^\circ\text{C}$ , except pyruvate, which was prepared fresh on the day of each experiment.

### Isolation of Mouse Liver Mitochondria

Mice were euthanized using isoflurane in accordance with IACUC procedures. Mitochondria were isolated by a method similar to Schnaitman and Greenawalt<sup>2</sup>. The liver was extracted and minced in ~10 volumes of MSHE+BSA at 4 °C, and all subsequent steps of the preparation were performed on ice. The material was rinsed several times to remove blood. The tissue was then homogenized using a drill-driven Teflon dounce homogenizer for 2–3 strokes. Homogenate was centrifuged at 800 g for 10 minutes at 4 °C. Following centrifugation, fat/lipid was carefully aspirated, and the remaining supernatant was decanted through two layers of cheesecloth to a separate tube, and centrifuged at 8,000 g for 10 minutes at 4 °C. After removal of the light layer, the final pellet was resuspended in a minimal volume of MSHE+BSA. Total protein (mg/mL) was determined using the Bradford Assay reagent (Bio-Rad).

### XF Assay Preparation

To minimize variability between wells, mitochondria were first diluted 10x in cold 1x MAS + substrate, then subsequently diluted to the needed concentration required for plating. Note that substrate

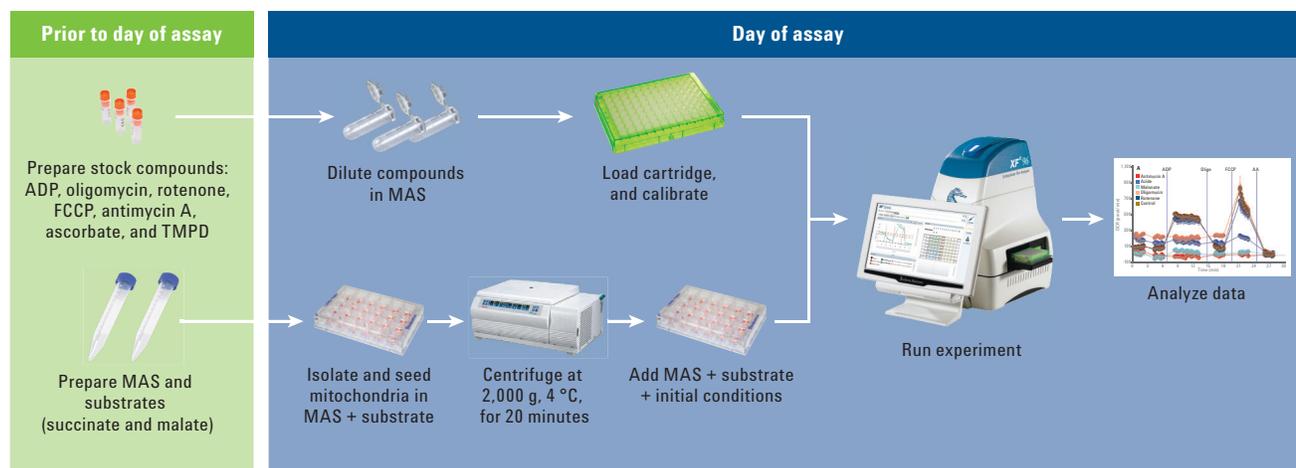


Figure 1. Flow chart of the XF assay.

is included in the initial dilution, and is present during the centrifugation step. Next, 25  $\mu\text{L}$  of mitochondrial suspension was delivered to each well (except for background correction wells) while the microplate plate was on ice. The Seahorse XF96 Cell Culture Microplate was then transferred to a centrifuge equipped with a swinging bucket microplate adaptor, and spun at 2,000 g for 20 minutes at 4  $^{\circ}\text{C}$ . After centrifugation, 155  $\mu\text{L}$  of prewarmed (37  $^{\circ}\text{C}$ ) 1x MAS + substrate + initial conditions (if applicable) was added to each well. The mitochondria were viewed briefly under a microscope at 20x to ensure consistent adherence to the well. The plate was then transferred to the Agilent Seahorse XFe/XF96 Analyzer, and the experiment initiated.

## Coupling Assay

This experiment examines the degree of coupling between the electron transport chain (ETC), and the oxidative phosphorylation machinery (OXPHOS), and can distinguish between ETC and OXPHOS with respect to mitochondrial function/dysfunction. Mitochondria (2  $\mu\text{g}$ /well; note: 2–3  $\mu\text{g}$  mouse liver mitochondria or 1–2  $\mu\text{g}$  rat heart mitochondria work well in the Agilent Seahorse XF96, respectively for succinate) begin in a coupled state with substrate present, in this case, succinate (10 mM) and rotenone (2  $\mu\text{M}$ ) (State 2). State 3 initiated with ADP, State 4 induced with the addition of oligomycin (State 4o), and FCCP-induced maximal uncoupler-stimulated respiration (State 3u) were sequentially measured, allowing respiratory control ratios (RCR: State 3/State 4o, or State 3u/State 4o) to be assessed as previously described<sup>4,5</sup>. Injections were as follows: port A, 20  $\mu\text{L}$  of 40 mM ADP (4 mM, final); port B, 22  $\mu\text{L}$  of 25  $\mu\text{g}/\text{mL}$  oligomycin (2.5  $\mu\text{g}/\text{mL}$ , final); port C, 24  $\mu\text{L}$  of 40  $\mu\text{M}$  FCCP (4  $\mu\text{M}$ , final); and port D, 26  $\mu\text{L}$  of 40  $\mu\text{M}$  antimycin A (4  $\mu\text{M}$ , final). (The final volume of the assay will be 272  $\mu\text{L}$ , which translates to  $\sim 10\times$  dilutions for ports A, B, C, D, respectively, Figure 2A).

## Electron Flow Assay

This experiment examines sequential electron flow through different complexes of the electron transport chain, which can identify the mechanism of mitochondrial dysfunction or modulation (Figure 2B). With the initial presence of 2  $\mu\text{g}$  mitochondria per well, 10 mM pyruvate, 2 mM malate, and 4  $\mu\text{M}$  FCCP, injections were made as follows:

- **Port A:** 20  $\mu\text{L}$  of 20  $\mu\text{M}$  rotenone (2  $\mu\text{M}$ , final)
- **Port B:** 22  $\mu\text{L}$  of 100 mM succinate (10 mM, final)

- **Port C:** 24  $\mu\text{L}$  of 40  $\mu\text{M}$  antimycin A (4  $\mu\text{M}$ , final)
- **Port D:** 26  $\mu\text{L}$  of 100 mM ascorbate plus 1 mM TMPD (10 mM and 100  $\mu\text{M}$  final, respectively).

Typical mix and measurement cycle times for the assays are illustrated in Table 1, and are common to all experiments presented unless otherwise noted.

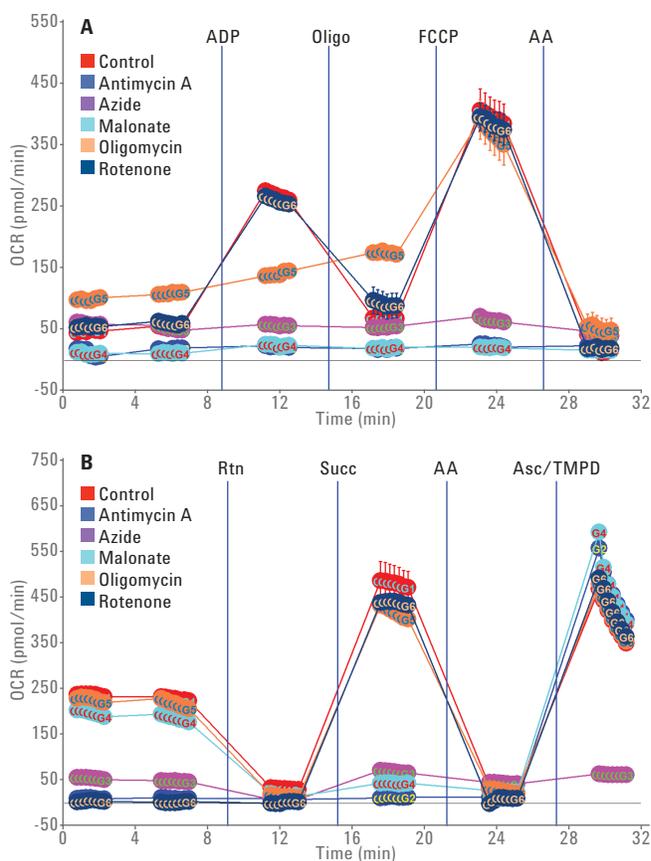


Figure 2. Determining mechanism of altered mitochondrial function using the coupling and electron flow assays in tandem to elucidate mechanistic activity of agents that perturb mitochondrial function. Coupling (A) and electron flow experiments (B) were performed as described in Methods. Initial conditions are as follows: Controls (no additives), 4  $\mu\text{M}$  antimycin-A, or 20 mM sodium azide, or 10 mM malonate, or 2.5  $\mu\text{g}/\text{mL}$  oligomycin or 2  $\mu\text{M}$  rotenone.

Table 1. Instrument run protocol.

| Start protocol |            |      |
|----------------|------------|------|
| Command        | Time (min) | Port |
| Calibrate      |            |      |
| Wait           | 10         |      |
| Mix            | 1          |      |
| Wait           | 3          |      |
| Mix            | 1          |      |
| Wait           | 3          |      |
| Mix            | 1          |      |
| Measure        | 3          |      |
| Mix            | 1          |      |
| Measure        | 3          |      |
| Mix            | 1          |      |
| Inject         |            | A    |
| Mix            | 1          |      |
| Measure        | 3–6        |      |
| Mix            | 1          |      |
| Inject         |            | B    |
| Mix            | 1          |      |
| Measure        | 3          |      |
| Mix            | 1          |      |
| Inject         |            | C    |
| Mix            | 1          |      |
| Measure        | 3          |      |
| Mix            | 1          |      |
| Inject         |            | D    |
| Mix            | 1          |      |
| Measure        | 3          |      |
| End protocol   |            |      |

## Data Analysis

All data were analyzed using Wave, and displayed as either point-to-point OCRs (pmol/min/well), or absolute oxygen tension in mmHg vs. time. Data are presented as the average of 3–5 replicate wells  $\pm$ SEM.

## Interpretation of Results

By using the two assays described, coupling and electron flow, it becomes possible to pinpoint the mechanism of unknown compounds, or genetic manipulation, on mitochondrial function (Figure 2). To illustrate the method, five well-described compounds that affect mitochondrial function were supplemented as *initial conditions*.

Inclusion of rotenone in the initial conditions showed no effect on the OCR values in the coupling experiment, as rotenone is already present and respiration is being driven by Complex II–IV activity. However, it was observed that in the electron flow experiment that pyruvate/malate-dependent respiration is inhibited at the beginning of the assay in contrast to the control, in which robust respiration is present. The fact that the control and the rotenone group show identical responses upon subsequent injections illustrates that the remainder of the electron transport chain is functioning properly.

Malonate is a competitive inhibitor of succinate dehydrogenase, a component of complex II, and antimycin inhibits complex III. For malonate, all the respiratory rates are inhibited as anticipated except for complex I-driven respiration at the start of the electron flow experiment, and the ascorbate/TMPD-driven respiration mediated by complex IV. As with malonate, the effects of antimycin A on the coupling portion show complete inhibition and no response to ADP, oligomycin, or FCCP. However, unlike malonate, antimycin A prevents both complex I- and II-mediated respiration due to inhibition of complex III, resulting in loss of activity throughout the electron flow portion of the assay until the addition of ascorbate and TMPD, indicating that complex IV remains active.

Azide inhibition of complex IV is demonstrated in both the coupling and electron flow experiments, with reduced respiration throughout the assay. Most instructive is the fact that addition of ascorbate and TMPD could not increase electron flow (and thus O<sub>2</sub> consumption) at complex IV. Finally, oligomycin, an inhibitor of the ATP synthase (complex V) prevents only ATP synthesis, the ADP-stimulated rate, in the coupling experiment, but does not affect electron flow among the complexes.

## Assay Optimization with Other Mitochondria Sources

When adapting this method to mitochondria isolated from other species/tissues, it is critical to ensure that an optimal amount of mitochondria are used per well. First, titrate the quantity of mitochondria to be used per well to ensure OCR values are within the linear range of response of the mitochondria, and within the dynamic range of the instrument (Figure 3A). State 2 rates should be kept between 40–80 pmol/min/well. Typically, 0.5–5  $\mu$ g of isolated mitochondria is a good range for optimizing of the assay, but more may be required depending on mitochondrial activity, quality, and purity.

If OCR results show high State 2 rates or poor response to ADP or other compounds (16  $\mu$ g, Figure 3A), it is likely that too much mitochondria is being used per well. In all cases, it is imperative to review the absolute O<sub>2</sub> tension data. Figure 3B illustrates the result of overloading the well, and shows complete depletion with mouse liver mitochondria samples of more than 4  $\mu$ g/well (O<sub>2</sub> tension approaches or reaches zero). Sensors do not have adequate time to return to ambient O<sub>2</sub> tension before the next measurement cycle, as evidenced by the steady decline in O<sub>2</sub> tension for each successive measurement cycle. These two factors prevent accurate measurement of OCR, with State 3 being underestimated and apparent poor response of the mitochondria to oligomycin and FCCP.

Use saturating concentrations of ADP to ensure the maximal State 3 rate is obtained for the duration of the measurement cycle (that is, the State 3 rate does not decline as judged by point-to-point data). Typically, 2–4 mM ADP is sufficient for saturation (Figure 4). Note that relatively high concentrations of ADP (1–4 mM) are needed to sustain stable State 3 respiration due to the very small microchamber formed during the measurement period.

Using lower concentrations (0.125–1.0 mM) will result in depletion of ADP during this time period. By obtaining stable OCR values for State 3, followed by determination of State 4o respiration, a respiratory control ratio (RCR value) may be calculated as  $3/4o$  (in this example,  $(280 \text{ pmol/min})/(64 \text{ pmol/min})$  or  $\sim 4.4$ ).

### Assay Optimization Hints

- While this Application Note uses actions of known compounds to demonstrate the utility of the coupling and electron flow assays, the same strategy may be applied to compounds of unknown function or tissue subject to genetic manipulations.
- This method does not employ the use of plate coating. Adapting these methods to utilize mitochondria from different tissues/species, relative purity level (for example, percoll gradient isolation), or assay solutions containing KCl may require the use of polyethyleneimine (Gerenser; *et al.* 2009)<sup>3</sup> or other coating to ensure adequate adhesion to the well plate.
- Centrifugation in larger volumes of mitochondrial suspension results in lower maximal respiratory rates, likely due to loss of mitochondria to the sides of the wells. Seeding 25  $\mu\text{L}$ /well is recommended. It is also recommended that a coupling experiment be performed in which all wells are treated identically to ensure consistency of mitochondrial adherence across the plate.

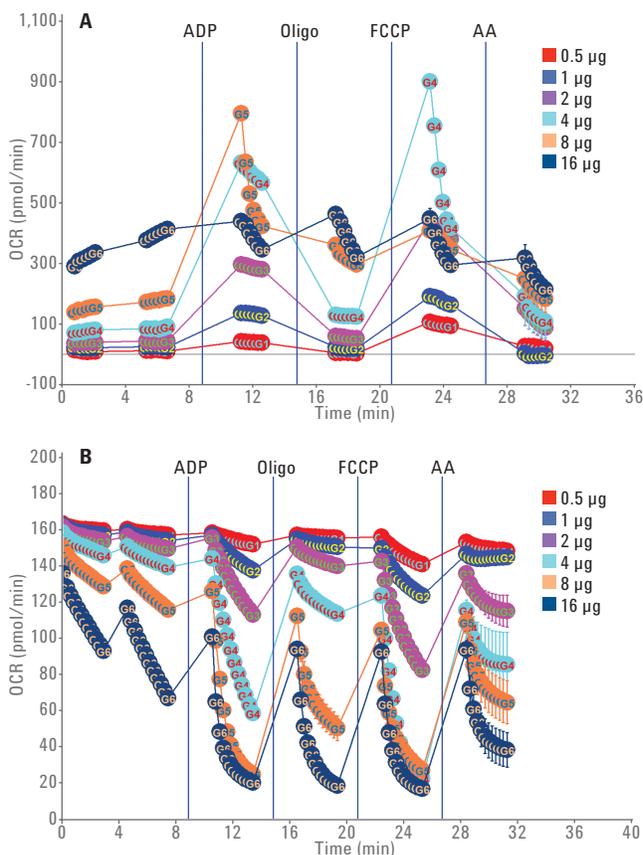


Figure 3. Determining optimal quantity of mitochondria. Using 0.5–16  $\mu\text{g}$  of mouse liver mitochondria attached to an XF96 Microplate, the coupling experiment was performed in the presence of succinate/rotenone as described in Methods. Blue vertical lines denote injections of indicated compounds. A) OCR for 0.5–16  $\mu\text{g}$  samples. B) the absolute O<sub>2</sub> tension (in mmHg) in the microchamber for 0.5–16  $\mu\text{g}$  samples. Note that samples at 4  $\mu\text{g}$  and above show unstable State 3 rates for OCR and depletion of O<sub>2</sub> in the microchamber.

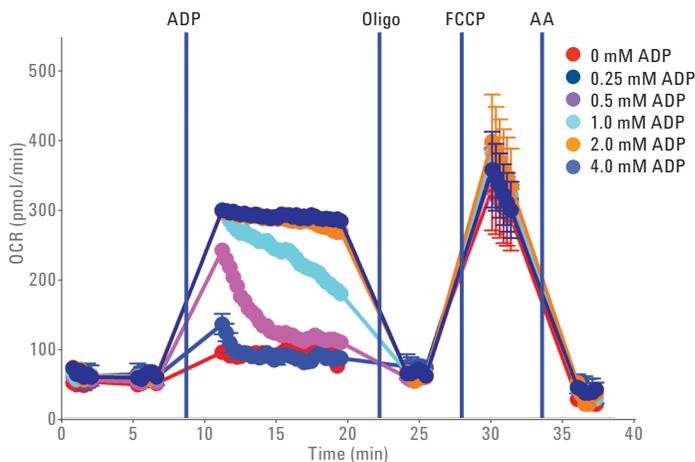


Figure 4. Determining optimal ADP concentration. Titration of ADP using 2  $\mu\text{g}$  of mouse liver mitochondria/well. ADP (0–4 mM) was injected via port A to initiate State 3 respiration and the measurement time was extended to 6 minutes. Note that 2–4 mM is sufficient to maintain a relatively stable rate of State 3 respiration rate for the duration of the measurement period, while lower concentrations show exhaustion of ADP and transition to State 4 respiration.

- In this Application Note, *substrate* refers to the carbon source provided for oxidation by mitochondria, including (but not limited to): succinate (10 mM)\*, glutamate/malate (10 mM each), pyruvate/malate (10/2 mM each), or palmitoyl carnitine/malate (40–80  $\mu$ M and 0.1–0.5 mM, respectively). It is imperative that substrate be included in the dilution and subsequent adherence of mitochondria to the XF microplate. This is to prevent or reduce any damage or loss of respiratory activity due to a potential mitochondrial permeability transition event. *Initial conditions* refer to any additional compounds that may affect mitochondrial function, and are included at 1.1x final concentration in the 155  $\mu$ L of MAS that is added to each well after the adherence step, but before inserted into the Seahorse XFe/XF96 Analyzer.
 

\* It is customary practice to include rotenone with succinate to prevent any Complex I driven respiration.
- The assays presented have been designed for the shortest duration possible, but note that more than one measurement cycle may be used after each injection to ensure kinetic equilibrium.
- Certain types or preparations of mitochondria can exhibit a run-down effect in respiration across the time frame of the coupling assay. Experiments have demonstrated that this effect can often be reduced/eliminated by initiating the coupling assay in the presence of ADP (State 3 respiration) due to the protective effects of adenine nucleotides on mitochondrial function. (that is, include ADP in the 155  $\mu$ L of assay buffer added to each well after the mitochondria are adhered to the microplate).
- Extending the measurement time for State 3 or lowering the concentration of ADP used, will show exhaustion of ADP, as is illustrated by the point-to-point rate data in Figure 4 (0.5–1.0 mM ADP and a measurement time of 6 minutes) The method provides the ability to record State 3 respiration followed by exhaustion of ADP to State 4.

## References

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